



## **Loads in wind farms under non-neutral ABL stability conditions: A full-scale validation study of the DWM model.**

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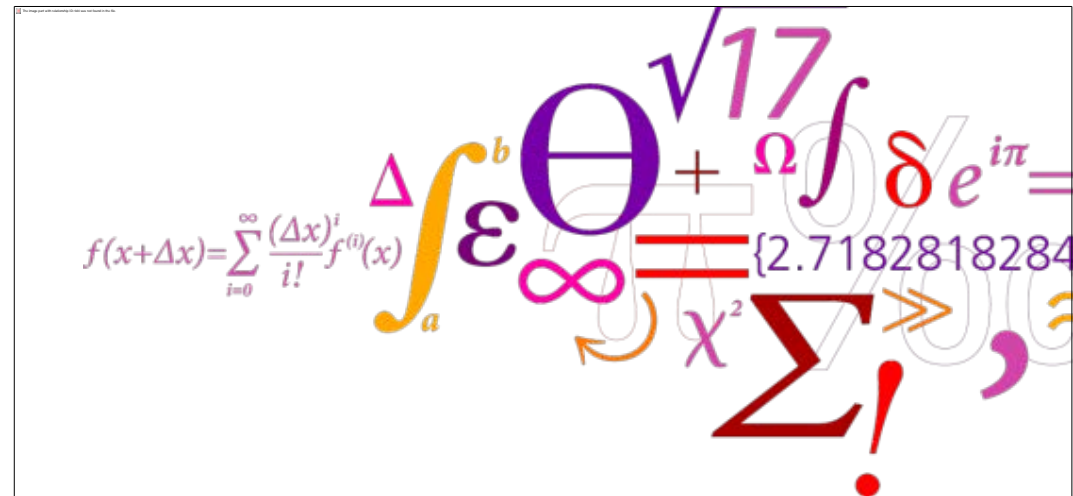
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# Loads in wind farms under non-neutral ABL stability conditions – a full-scale validation study of the DWM model

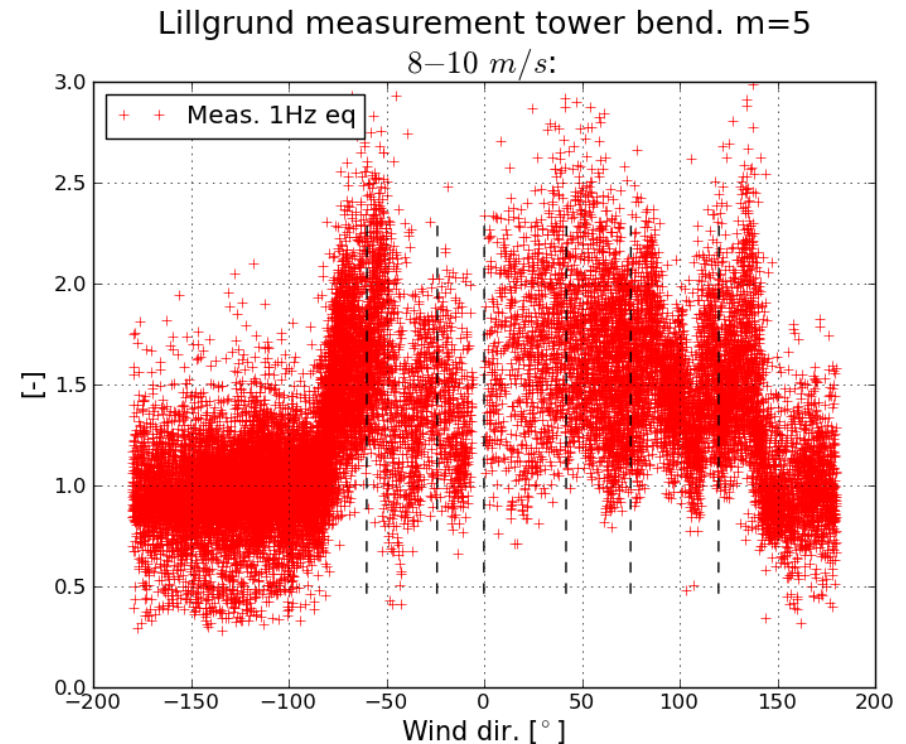
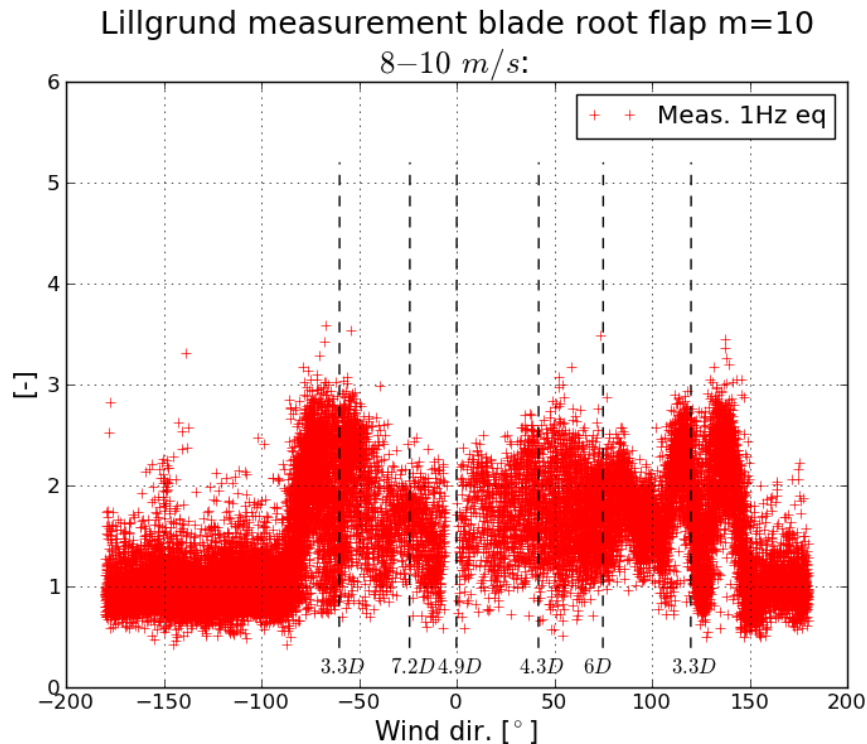
G.C. Larsen, T.J. Larsen, Søren Ott and K.S. Hansen



# Outline

- Motivation
- Hypothesis ... ABL stability
- DWM "classic"
- Approach ... DWM under non-neutral stability conditions
- Lillgrund WF case study
  - Layout
  - Stability classification
  - Results
  - Summary
- Conclusions
- Future work
- Acknowledgements

# Motivation (1) ... why non-neutral?

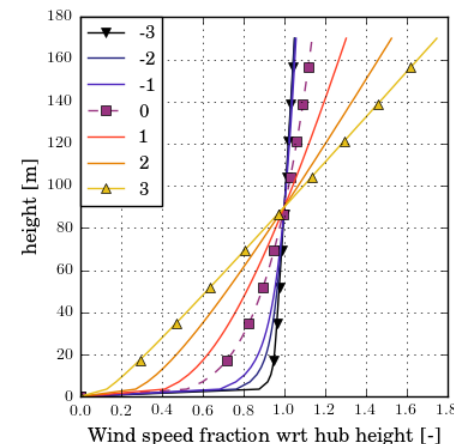


## Motivation (2) ... why medium fidelity?

- Non-stationary flow fields are required for WT **load estimation**
- High-fidelity CFD-LES modeling is CPU-costly and challenged by boundary conditions ... and a coupled aeroelastic/CFD-LES approach is **not** feasible for a large number of WF simulations!
- Need for medium-fidelity flow field models that
  - Preserves the **essential physics** of non-stationary wake flows
  - Is (relatively) **in-expensive**
  - Allow for a straight forward **coupling** with aeroelastic models

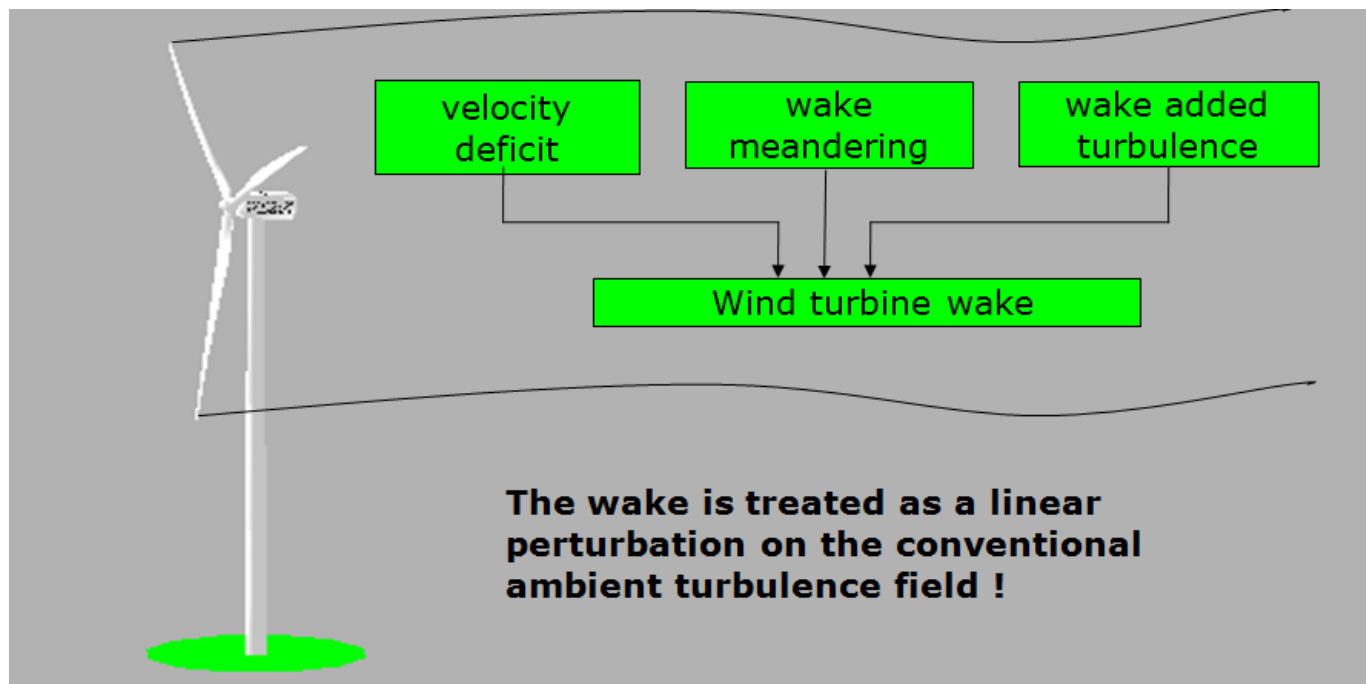
# ABL stability

- Mechanical friction is dictating turbulence production in the ABL under neutral conditions
- Buoyancy effects adds to friction when it comes to the turbulence production under non-neutral ABL stability conditions
- ABL stability implications
  - Increased/decreased turbulence intensity for unstable/stable conditions
  - Modified turbulence structure ... mainly in the large scale regime
  - Modified shear profile



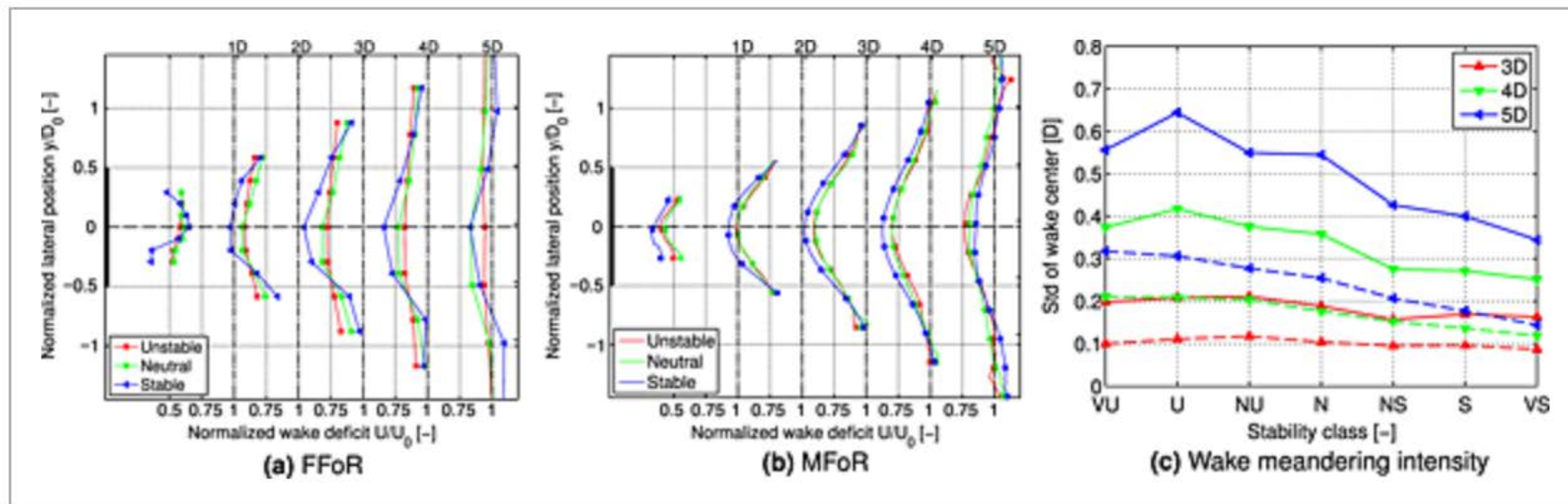
# DWM “classic”

- Included in the IEC-code as recommended practice
- “Poor man’s LES” ... based on a **passive tracer** analogy [Larsen GC et al.; Wake meandering – a pragmatic approach; WE]



# DWM under non-neutral stability conditions (1)

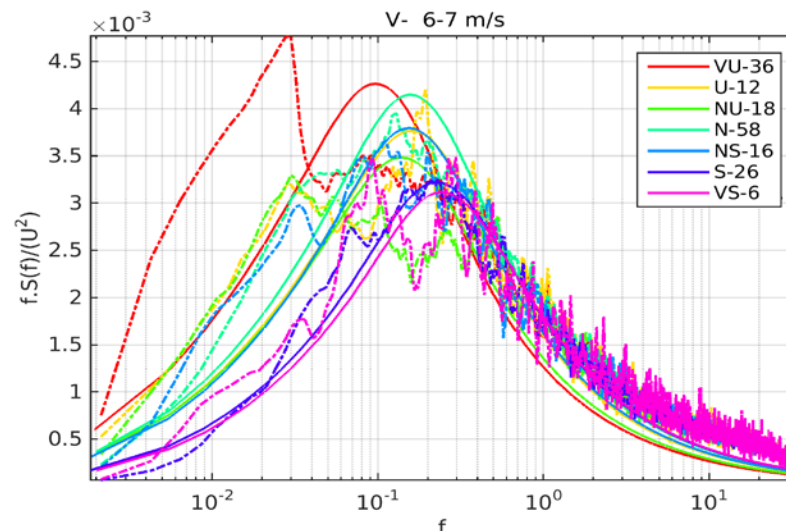
- Full-scale LiDAR experiments [Machefaux et al., WE; Larsen et al., Journal of Physics] have justified:
  - ABL stability impacts mainly the “large” (meandering) turbulence scales
  - “small” scale turbulence regime can be considered invariant with respect to ABL stability conditions





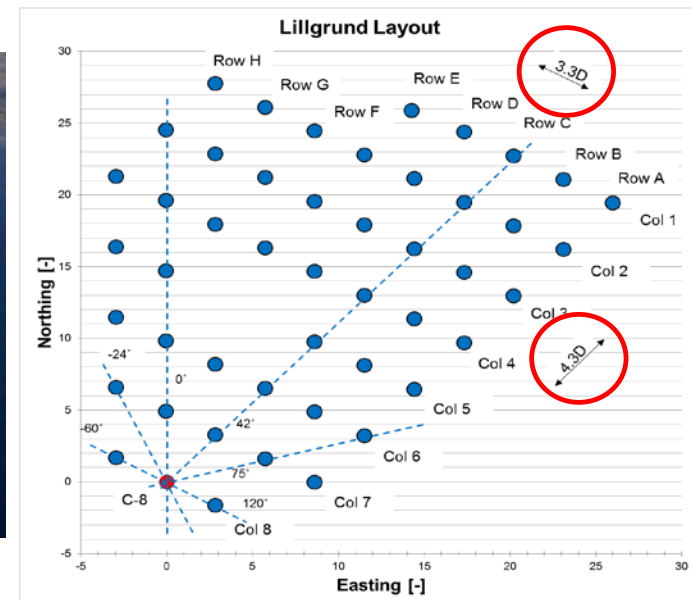
## DWM under non-neutral stability conditions (2)

- Synthetic turbulence fields are generated using a generalization of the Mann spectral tensor [Chougule A, Mann J, Kelly MC and Larsen GC; JAS]
  - Buoyancy included!
  - Homogeneous velocity and temperature fields
  - Turbulence production driven by vertical **shear** and a vertical **temperature** gradient



# Case study – Lillgrund WF

- Blade flap and tower bottom moments
- Turbine C-8
- 2008-06-03 to 2013-03-19 ... almost 5 years of data
- Un-stable, neutral and stable ABL conditions in focus ... but met. mast is missing 🙄



## Case study – the Drogden supplement 😄

- Offshore light tower ... a few km. WNW of the WF (about the characteristic scale of the WF)
- Available 10-min recordings
  - $U$  and  $T_a$  at  $h = 22\text{m}$
  - $T_w$  at  $h = -1\text{m}$
  - Appr. 15.600 hours of measurements (2008–2013)



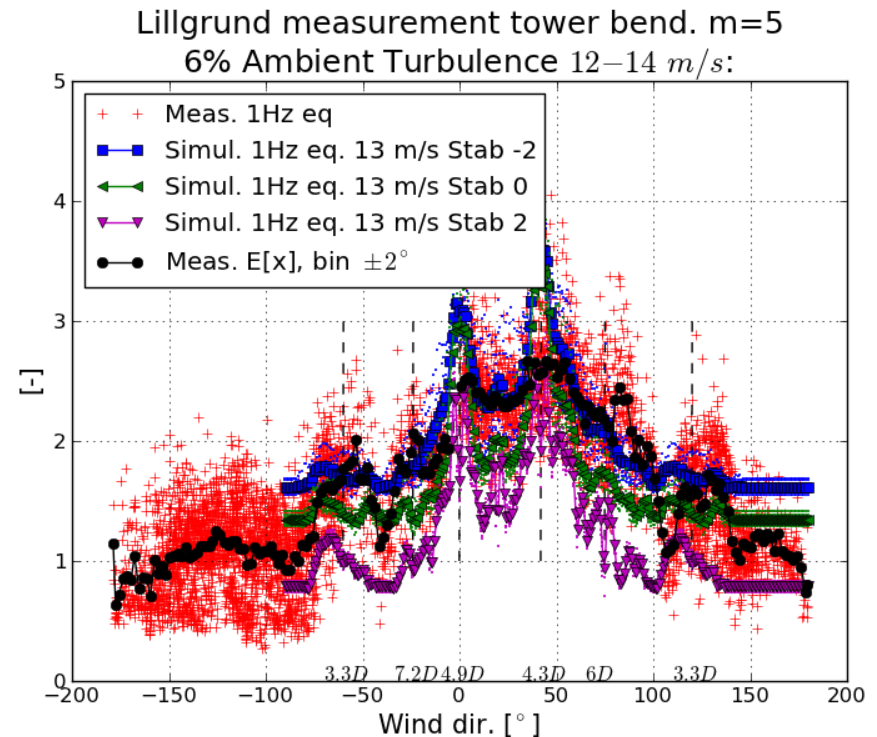
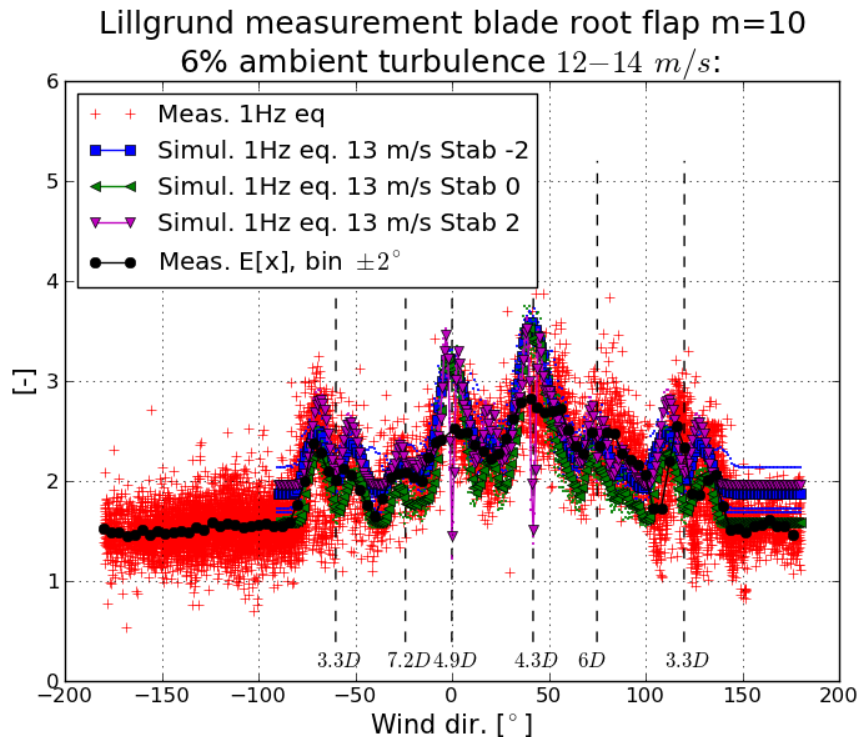
# Case study – stability classification

- AMOK approach for offshore sites [Larsen GC et al.; Impact of atmospheric stability conditions on wind farm loading and production; DTU report]
  - Based on a newly developed version of the M-O theory suited for 'tall' profiles
  - Profile functions  $\psi_m(z/L, \mu)$  and  $\psi_h(z/L, \mu)$  are complex with an unstable branch for  $z/L < 0$  and a stable branch for  $z/L > 0$  ...  $\mu$  Monin-Kazanski parameter
  - Needs:  $T_a$ ,  $U$ ,  $T_w$  ... e.g. from different heights
- Stability classes ( $1/L$ ) [Gryning et al.; BLM 124]

Stability Class <u>iC</u>	Description	Condition
-2	unstable	$-200\text{m} < L < -100\text{m}$
0	neutral	$500\text{m} <  L $
2	stable	$50\text{m} < L < 200\text{m}$

# Case study – Results (1)

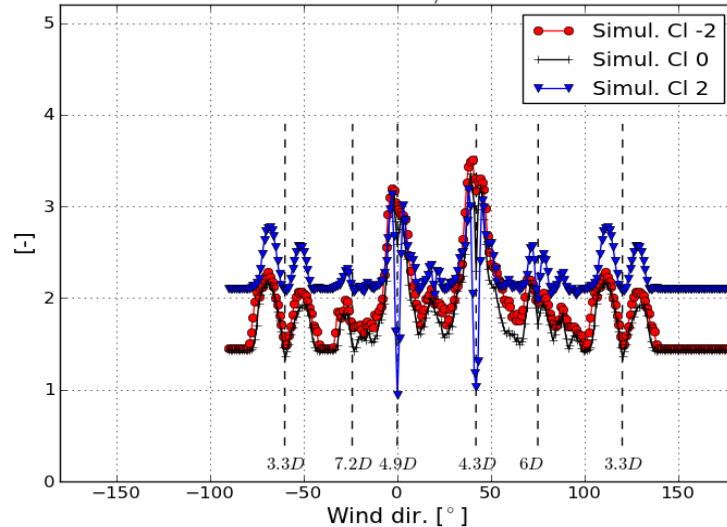
- Flap and tower bottom fatigue equivalent moments
  - 13m/s:



# Case study – Results (2)

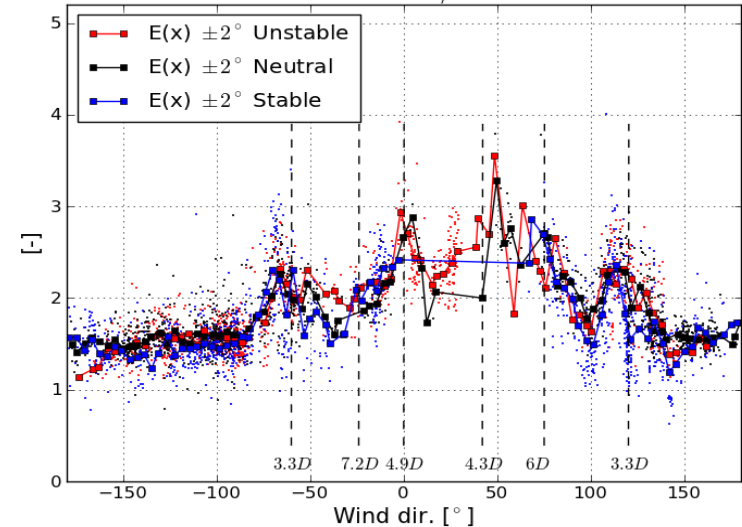
Lillgrund simulations blade root flap  $m=10$

12–14 m/s:



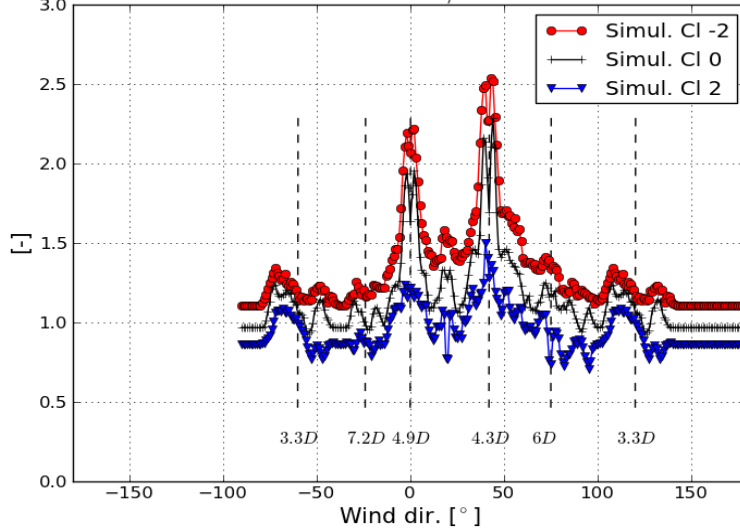
Lillgrund measurement blade root flap  $m=10$

12–14 m/s:



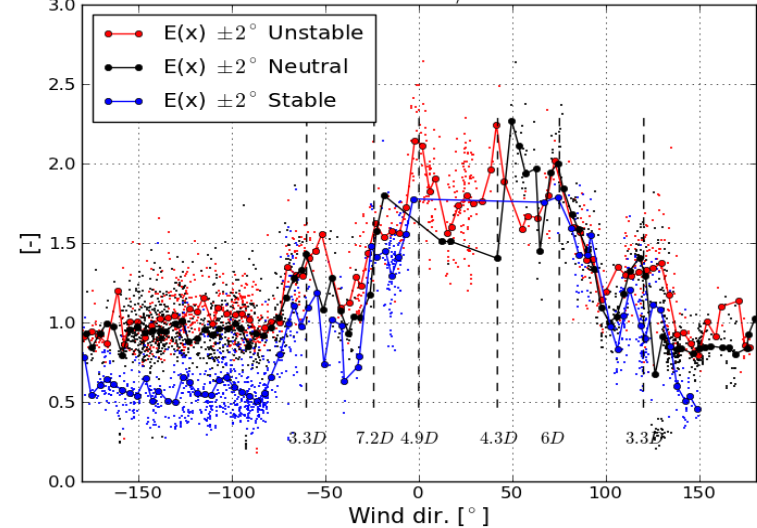
Lillgrund simulations tower F-A bottom  $m=4$

12–14 m/s:



Lillgrund measurement tower F-A bottom  $m=4$

12–14 m/s:

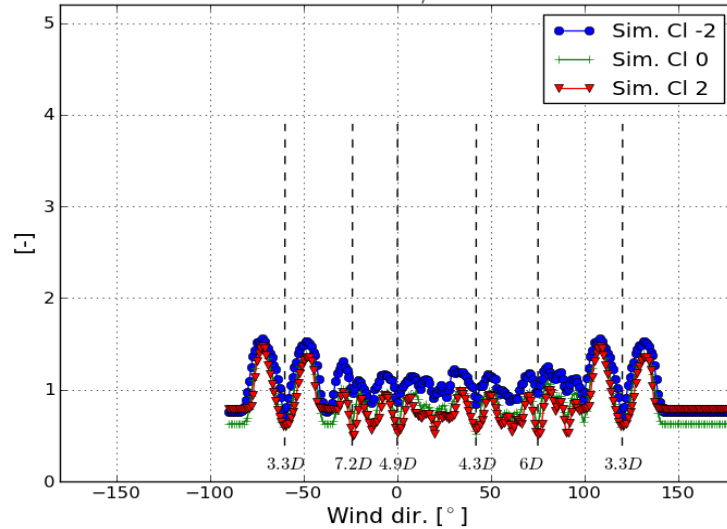




# Case study – Results (3)

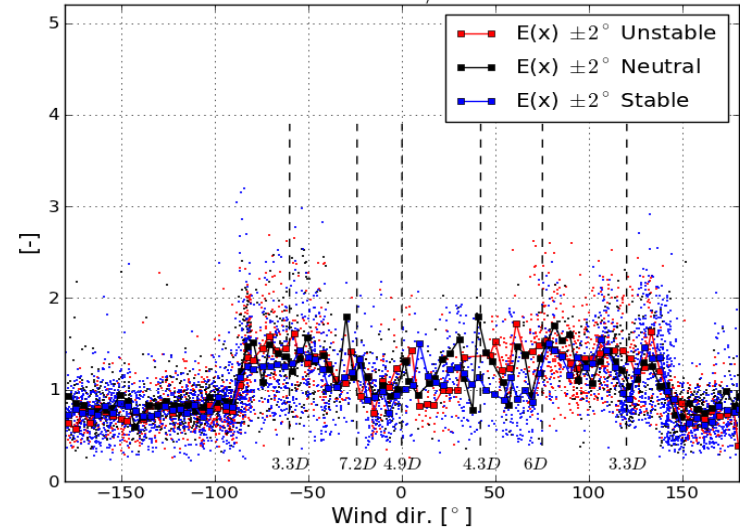
Lillgrund simulations blade root flap  $m=10$

6–8 m/s:



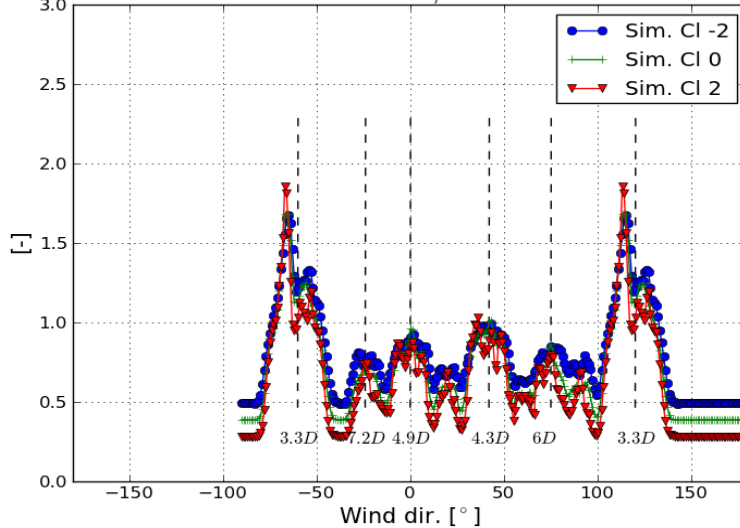
Lillgrund measurement blade root flap  $m=10$

6–8 m/s:



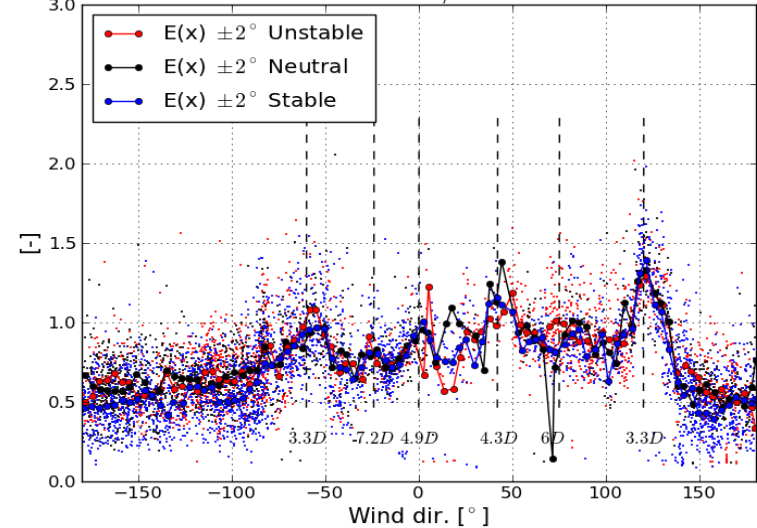
Lillgrund simulations tower F-A bottom  $m=4$

6–8 m/s:



Lillgrund measurement tower F-A bottom  $m=4$

6–8 m/s:



## Conclusions (1)

- A medium-fidelity non-stationary flow field approach for **non-neutral** ABL conditions is established and coupled with the aeroelastic code HAWC2
- The approach is CPU in-expensive compared to high-fidelity CFD LES ... and is potentially useful for WF layout optimization and WT control design (TOPFARM)
- Simulations:
  - For the **rotating** WT components the ABL stability impact on shear and turbulence has **contra-acting influences** on loading
  - **Shear** is the dominating fatigue load driver for the **rotating** WT components in the **high wind regime** ... otherwise turbulence incl. wake meandering



## Conclusions (2)

- Simulations:
  - Turbulence incl. wake meandering is the dominating load driver for tower fatigue loading
  - These observations are consistent with a load study of a solitary WT [A. Sathe et al., WE] ... but ABL stability impact on loading further enhanced in WF conditions due to wake dynamics
- Measurements:
  - Agrees reasonably well with simulations ... BUT the significant dependence of blade loading with shear is not seen!
  - Some uncertainty on mean values ... e.g. not “perfect” symmetry of 3.3D cases

## Future work

- Replace classic M-O profile functions with profile functions following from the modified version of the M-O theory suited for 'tall' profiles ... which displays less pronounced shear in the stable regime BUT include veer
- Example quantification of stochastic variability ... 20 seeds for one arbitrary wake affected inflow condition
- Mutual comparison of DTU (DWM/HAWC2) simulations, KUL (SPWind) simulations and full-scale Lillgrund measurements ... power; flap fatigue loading; tower, fatigue loading
- Consolidate Drogden based stability classification with WRF-simulations
- Inclusion of meso-scale effects in the DWM model approach ... the high frequency end of the meso-scale regime

# Acknowledgements

The EUDP project “Impact of atmospheric stability conditions on wind farm loading and production”, under contract 64010-0462, is acknowledged for financial support and thus for making this study possible.

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